8467

RI 8467

Bureau of Mines Report of Investigations/1980

Correlation of the Fibrous Aerosol Monitor With the Optical Membrane Filter Count Technique

By Steven J. Page

UNITED STATES DEPARTMENT OF THE INTERIOR

I 28.23

Report of Investigations 8467

Correlation of the Fibrous Aerosol Monitor With the Optical Membrane Filter Count Technique

By Steven J. Page

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES
Lindsay D. Norman, Acting Director

best copy available

This publication has been cataloged as follows:

Page, Steven J

Correlation of the fibrous aerosol monitor with the optical membrane filter count technique.

(Report of investigations - Bureau of Mines ; 8467)

Bibliography: p. 16-17.

Supt. of Docs. no.: I 28.23:8467.

1. Aerosols–Measurement–Instruments. I. Title. II. Series: United States. Bureau of Mines. Report of investigations ; 8467.

TN23.U43 [TD884.5] 622s [628.5'3'20287] 79-607903

CONTENTS

	Page
Abstract	1
Introduction	1
Acknowledgments	2
Fibrous aerosol monitor	3
Description	3
Theory of operation	4
Experimental procedure	5
Fibrous aerosol sampling	5
Tests using the fibrous aerosol monitor	6
Optical analysis	7
Data analysis	8
Discussion of results	12
Recommendations and conclusions	14
References	16
Appendix A.--Laboratory test facility	18
Appendix B.--Test data sheet	21

ILLUSTRATIONS

1.	Fibrous aerosol monitor	3
2.	Optical and flow design of the fibrous aerosol monitor	4
3.	Flow chart for fiber sampling system	6
4.	Linear least-squares regression for two fibrous aerosol monitors	12
A-1.	Fibrous aerosols as shown in scanning electron photomicrographs	18
A-2.	Flow chart for fiber generation system	19

TABLES

1.	Test summary for determination of ratio control setting	9
2.	Least-squares regression lines relating fiber concentrations determined by fibrous aerosol monitor and by optical count	9
3.	Test summary for linear regressions	11

CORRELATION OF THE FIBROUS AEROSOL MONITOR WITH THE OPTICAL MEMBRANE FILTER COUNT TECHNIQUE

by

Steven J. Page[1]

ABSTRACT

The Bureau of Mines used fiber-laden air to test two identical fibrous aerosol monitors (FAM) in order to establish the FAM-optical count correlation. The FAM is a unique instrument developed by GCA Corp. (GCA) to measure real-time fibrous aerosol concentrations. It will also respond to particulates that have sufficient shape irregularities to possess fiber characteristics such as the 3:1 length:diameter (L:D) aspect ratio.

Results of the Bureau's laboratory tests showed that the FAM response is linearly correlated to concentration data obtained using the optical membrane filter count technique approved by the National Institute for Occupational Safety and Health (NIOSH), U.S. Department of Health, Education, and Welfare. A plot of the FAM-optical count correlation showed that FAM concentration readings are generally well within ±25 pct of the optical membrane filter count.

Initial tests to estimate the best ratio control setting of the FAM for 5-μm fiber-length discrimination were performed using one instrument only (the ratio control setting determines the minimum threshold fiber length that will be detected by the FAM). The estimated setting was then used to correlate both FAM units. The result was a 65 pct difference in correlation between the two units. It appears that the major factor responsible for this difference was the internal adjustment of the photomultiplier detector sensitivity for each of the two FAM units.

INTRODUCTION

Since 1946, recommendations have been made in favor of low-risk threshold limit values (TLV) of asbestos dust in the workplace (9).[2] Asbestos dust has been recognized as a carcinogen responsible for causing such respiratory diseases in humans as asbestosis and lung cancer (2). More recently, other fibrous substances such as fibrous glass and asbestiform minerals associated with talc deposits have been suspected of inducing respiratory disease (1, 4, 11).

---

[1]Physicist, Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

[2]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

READEX FICHE

The continuing trend to reduce the recommended TLV for asbestos exposure during an 8-hour working shift (10) is reflected in the following statement from the December 1971 Federal Register (16):

> The 8-hour time-weighted average (TWA) airborne concentration of asbestos dust to which employees are exposed shall not exceed 5 fibers per milliliter greater than 5 microns in length, as determined by the membrane filter method at 400-450x magnification (4 millimeter objective) phase contrast illumination. Concentrations above 5 fibers per milliliter, but not to exceed 10 fibers per milliliter, may be permitted up to a total of 15 minutes in an hour for up to 5 hours in an 8-hour day.

This became the standard promulgated by the Occupational Safety and Health Administration, U.S. Department of Labor, on June 7, 1972. On July 1, 1976, following a recommendation by NIOSH, the 8-hour exposure standard for asbestos was again lowered, this time to 2 fibers/ml (29 CRF 1910.1001).

More recent recommendations have called for lowering the 8-hour standard TWA to 0.5 fibers/ml, and a 0.1-fiber/ml standard has also been recommended.

The standard NIOSH-approved optical membrane filter count has several drawbacks that severely impair the assessment of occupational and/or environmental conditions that may require rapid corrective or protective measures. Variations in microscope calibrations, sample preparation, and human interpretation may cause errors of ±50 pct or more (6). Furthermore, the delay between the time the sample is obtained and its subsequent analysis may be days.

The continuing trend to reduce the 8-hour TWA has led to an increasing need for real-time fibrous dust concentration estimates. It was the need for concentration estimates of this kind that resulted in the development of the FAM (7). The FAM was developed through joint funding provided by the Bureau of Mines and NIOSH. Subsequently, the Bureau evaluated the FAM-optical count correlation, using laboratory tests conducted at the Bureau's Pittsburgh Research Center (PRC) as the basis for its evaluation. The object of this evaluation was to assess the current state-of-the-art in real-time asbestos sampling, and the Bureau's findings are presented in this report.

Some previous work to determine the FAM-optical count correlation has been done by GCA, the developer of the FAM (5); but this work was not extensive and has not been published. GCA's work included a correlation based on field testing, but the data from the field did not correlate as well as when the FAM and optical count method were tested in the laboratory.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of his colleagues at the PRC, James V. Derby, research chemist, for the optical analysis of the samples; Daniel Ng, research physicist, for the scanning electron microscope photography; and Jon C. Volkwein, physical scientist, for numerous private discussions.

FIBROUS AEROSOL MONITOR

Description

The model FAM-I fibrous aerosol monitor developed by GCA (fig. 1) is a unique portable instrument designed to provide real-time estimates of airborne concentrations of fiber-shaped particles. When equipped with a separate, optional charger-battery pack, the FAM is a fully self-contained unit capable of a minimum of 4 hours continuous duty. Without the battery pack, the unit requires either 115 v or 220 v, 50/60 Hz power. FAM units are factory-designed for 115 v, with 220 v units available upon request.

The FAM is 53 cm long, 35 cm deep, and 17 cm high (with cover); and it weighs 12.5 kg. The sampling flow rate is nominally 2 l/min and is continuously adjustable from 1.5 to 2.5 l/min. The sampling period is manually adjustable from the front panel and can be selected in tenfold increments between 1 min and 1,000 min. At the end of a sampling period, the fiber concentration is digitally displayed in fibers per milliliter. In addition to the digital fiber-count display, an analog readout can selectively provide outputs of battery voltage, rotating field voltage, laser power, total scattering signal, and the average scattering signal from fibrous particles only. Analog and digital recorders are available as optional peripheral accessories.

Ratio, amplitude, and photomultiplier gain functions are conveniently mounted on the front panel. Fine adjustment of the ratio and amplitude functions is accomplished with 10-turn potentiometers.

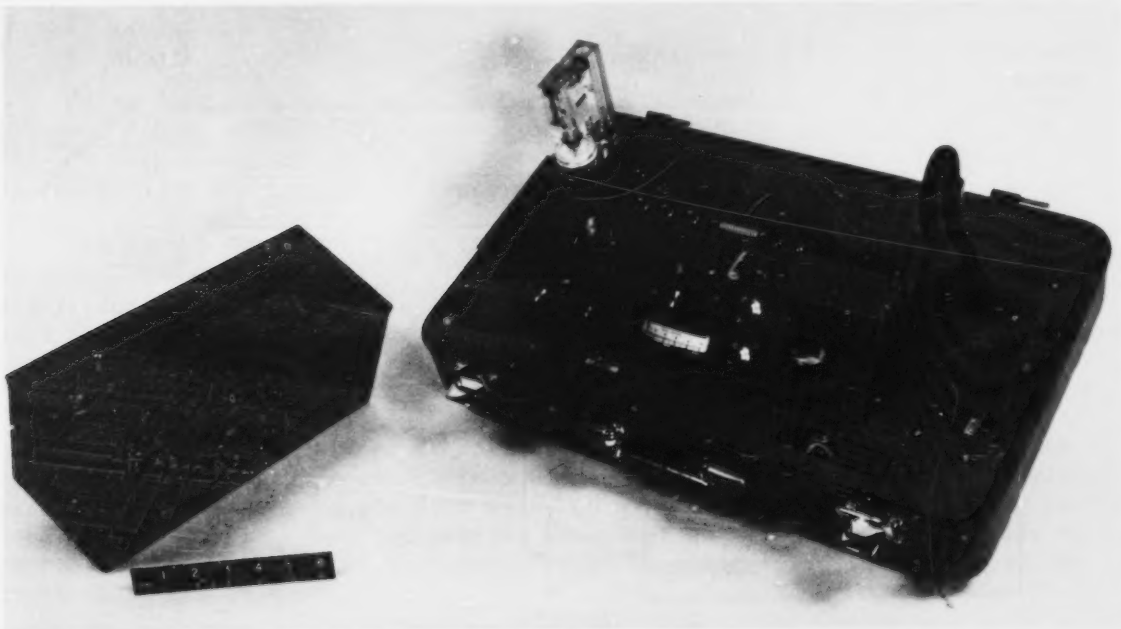

FIGURE 1. - Fibrous aerosol monitor. (Scale is in inches.)

A standard 35-mm membrane filter cassette assembly is incorporated into the FAM flow path downstream of the fiber detection volume and is readily accessible on the instrument panel. Overload lights to indicate saturated conditions with respect to fiber concentration and the photomultiplier detector are located on the front panel. An integral safety-interlock alarm that indicates the presence of exposed laser radiation brings the FAM into compliance with requirements of the Bureau of Radiological Health, U.S. Department of Health, Education, and Welfare.

A warm-up period is recommended prior to sampling. This period should last approximately 10 min, or until output indicated by the laser power meter is near maximum. Maximum output is generally 5 v ±0.5 v.

Theory of Operation (7)

The unique combination of operating principles incorporated into the FAM includes phenomena such as electrostatic fiber polarizability, electric field-induced synchronous fiber rotation, and scattering pulse-shape discrimination. Figure 2 illustrates the internal flow and optical design of the FAM.

Operation of the FAM involves a two-step sensing procedure. First, the sampled fibers are induced to rotate rapidly by the application of a rotating

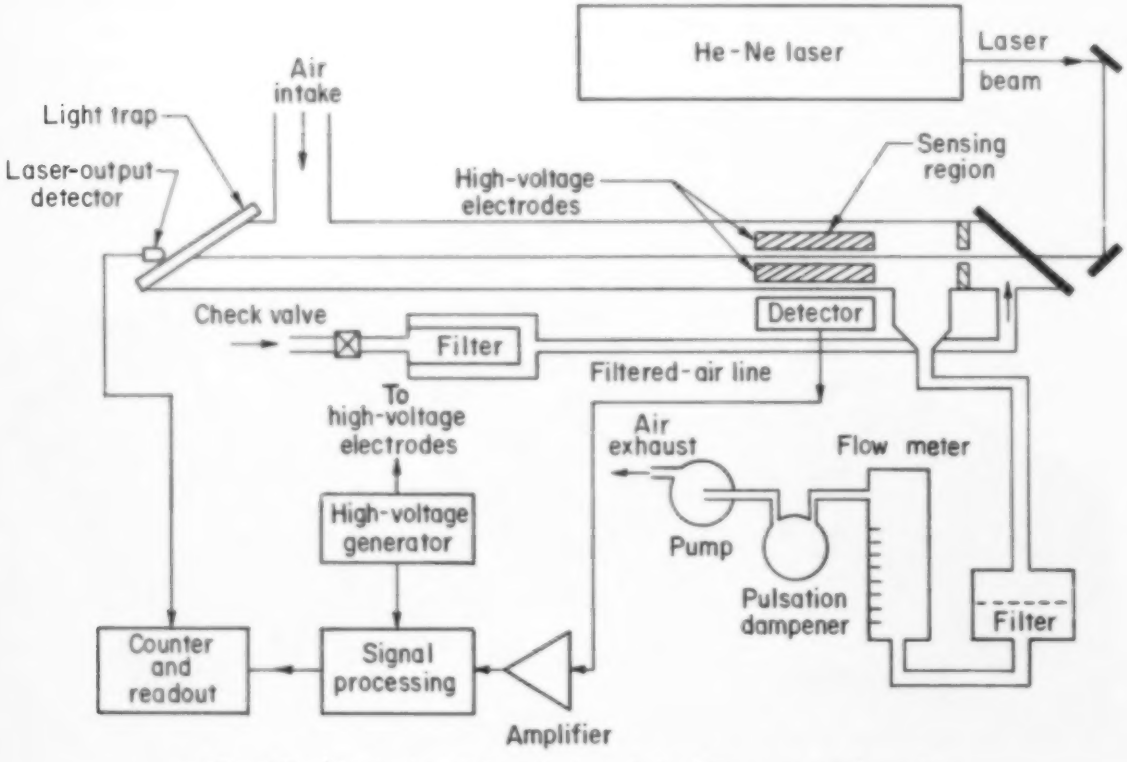

FIGURE 2. - Optical and flow design of the fibrous aerosol monitor.

high-intensity electric field. Then, the light-scattering signature associated with these fibers is detected while they are illuminated by a monochromatic light beam from a laser. A 2-mw helium-neon laser operating at 632.8 nm (nanometer) wavelength provides scattering illumination.

Because the frequency of the light-scattering pulses produced in this manner is known, synchronous electronic signal detection can be used to greatly enhance the signal-to-noise ratio. Each fiber generates a pulse train as it rotates in a helical trajectory that results from the combined effects of the recilinear airflow[3] and the perpendicular field-induced rotation. Because longer fibers produce narrower pulses than shorter ones, the FAM is able to discriminate between fibers of different lengths by sensing the sharpness of individual pulses.

The fundamental assumption concerning fiber shape is that it is approximately cylindrical. In general, fibrous aerosols such as those consisting of fibrous glass or amosite, crocidolite, or anthophyllite asbestos meet this cylindrical criterion. Therefore, the complex problem of light scattering from these fibers can be theoretically approximated. To reduce the problem complexity even further, it is assumed that the scattered light is detected at a fixed right angle to the laser illumination and that this laser illumination is always at right angles to the plane of fiber rotation. The above special case of light scattering has been studied extensively (3, 14). A more detailed description of the theory of operation can be found in the GCA final contract report (7).

EXPERIMENTAL PROCEDURE

Fibrous Aerosol Sampling

Fiber dust samples were collected as recommended by the NIOSH-approved membrane filter sampling procedure (15) illustrated in figure 3. The dust samples were then used as the FAM reference standard. (For a complete description of the laboratory test facility, see Appendix A.)

The fibers were then collected on the type of filter that is recommended by NIOSH, the Millipore[4] type AA membrane filter (37-mm diam, 0.8 μm pore size), and mounted in open-faced cassettes using standard backup filters. Each filter assembly was charge-neutralized with an antistatic bar--both before and after sampling--to eliminate static attraction of fibers.

A vacuum pump rated at 0.03 m^3/min at 508 mm Hg provided sufficient pressure differential across a critical orifice to maintain a sampling flow rate of 2 l/min, determined within ± 0.5 pct with a wet-test meter. Sampling periods for each test ranged from 15 to 60 min, depending on the aerosol concentration sampled. Sampling periods were kept short to avoid fiber pile-up on the filter, a source of systematic error when the optical membrane filter count technique is used.

---

[3]Airflow profile is laminar, fully-developed, and parabolic.

[4]Reference to specific trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

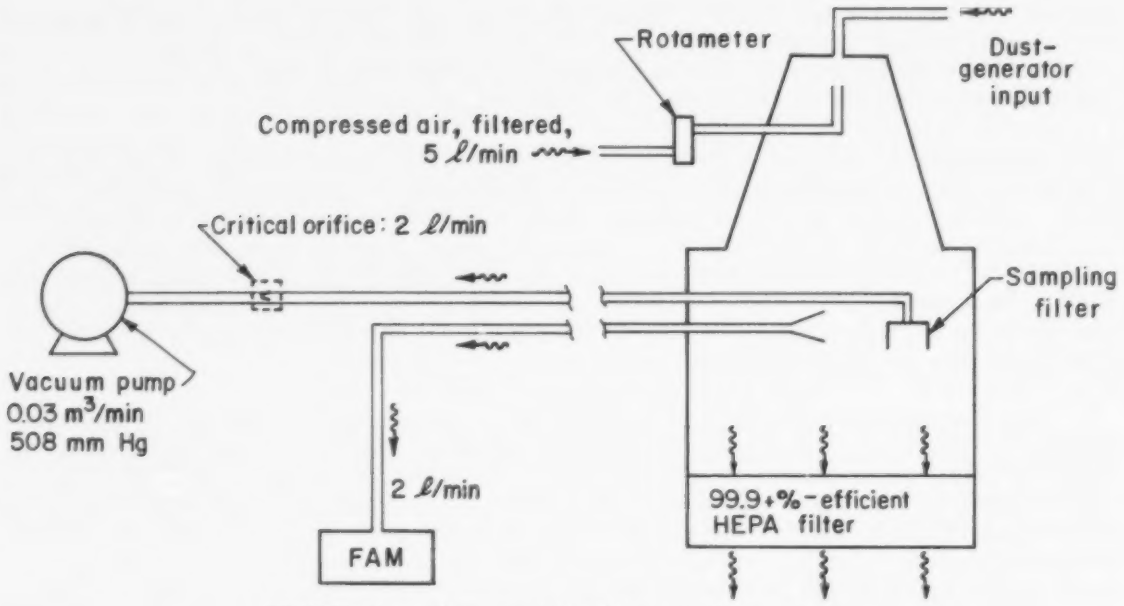

FIGURE 3. - Flow chart for fiber sampling system.

Tests Using the Fibrous Aerosol Monitor

The FAM was used to monitor fiber concentrations in the aerosol concurrently with the membrane filter sampling. The unit was operated in either the 1-min or 10-min counting mode, depending on the length of the corresponding membrane sampling period. At the end of each counting interval, the measured fiber concentration was recorded and averaged with measurements from the other counting intervals for the same test. The FAM flow rate was set and maintained at 2 l/min throughout each test. A sample test data sheet is shown in Appendix B.

The FAM sampled the aerosol within 20 cm of the membrane filter cassette through an expanded orifice that had the same diameter as the cassette. Previous gravimetric sampling at 24 locations within the test chamber indicated an 11.4 pct coefficient of variation in fiber concentration. FAM diagnostic readings, such as field voltage, laser power, and photomultiplier current, were frequently monitored and recorded for each test.

The FAM-optical count correlation was established by a two-step procedure designed to take into consideration the FAM's variable-control features, which substantially affected the correlation. The two steps are described below:

1. To obtain the best estimate of the ratio control[5] setting, 3 tests using different concentrations in the range from 0 to 10 fibers/ml were run for each of 5 different ratio settings.

2. To obtain the FAM-optical count correlation determined by this best estimate for the ratio control setting, a series of tests using different concentrations in the range from 0 to 10 fibers/ml was run, holding the ratio control setting constant.

The setting for the amplitude function was fixed at 0.20 for all tests. This value is approximately the same as the setting recommended by the manufacturer and is used as an arbitrary level discriminator to eliminate spurious counts produced by scattered stray light, electronic noise, etc.

The purpose of the two-step procedure is to establish the proper correlation for approximate 5-μm fiber-length discrimination. This procedure minimizes the possibility of counting fibers less than 5 μm in length or not counting fibers greater than 5 μm in length.

The FAM is essentially a fixed fiber-length discriminator, and its fiber-length cutoff point is dependent upon the ratio control setting. Although an arbitrary ratio control setting would provide a linear FAM-optical correlation, there would be no guarantee that the FAM was not counting fibers shorter than 5 μm or counting all fibers longer than 5 μm. An arbitrary adjustment of the FAM would be satisfactory if all fibrous aerosols had the same size distribution, because a fixed number proportion between fiber sizes would be guaranteed. But because fiber size distributions do vary, it is necessary to obtain a reasonable estimate of the ratio control setting that most closely approximates the optical membrane filter count in order to establish the FAM-optical count correlation.

Optical Analysis

NIOSH recommendations were followed for the collection, preparation, and optical analysis of the membrane filter samples. Fiber samples were collected as previously described (15), then mounted on microscopic slides for optical analysis. Microscopic field fiber counts were then used to determine fiber concentrations of the aerosol samples.

The mounting medium was prepared by dissolving a portion of the membrane filter in a 1:1 solution of dimethyl phthalate and diethyl oxylate. The filter-to-solution proportion of this medium was 0.05 g/ml, and the resulting medium had an index of refraction of 1.47. A drop in the mounting medium was placed on a freshly cleaned standard 25- by 75-mm microscope slide. A 20- by

[5]The term ratio control should not be misinterpreted. In this sense, ratio does not imply fiber length:diameter aspect ratio. Rather, it is a number that specifies the detected pulse shape and is a threshold value directly related to fiber length, independent of fiber diameter. Hereafter, all references to the fiber length:diameter ratio will be referred to as the aspect ratio.

20-mm section was excised from the central portion of each test filter and placed fiber-side up on the mounting medium. A freshly cleaned No. 1 cover slip was placed over the filter section, and slight pressure was applied to the cover slip so that it contacted the mounting medium.

When this procedure is followed, the mount soon becomes transparent. Optical homogeneity is excellent once this occurs, and the sample is then ready for examination. The mount may have a slightly granular background, but this will disappear within one day.

Optical analysis of the mounted sample was based on the assumption that the collected fibers were uniformly distributed over the entire filter. This assumption is valid when sampling with open-faced filter cassettes. The effective area for the type of filter used was 855 mm^2.

A standard phase-contrast microscope equipped with Koehler illumination, X 10 eyepieces, X 40 achromatic objective, and calibrated Porton reticle was used. The Porton reticle, calibrated with a stage micrometer graduated in units of 10 μm, had a counting-field area of 0.0026 mm^2. This area will vary when different reticles or microscopes are used. Fields counted must be chosen at random to eliminate any human bias that might result in a preference for areas with a larger number of fibers.

DATA ANALYSIS

Since the method of analysis used to determine the fiber concentration for each test was a counting procedure, the statistical accuracy followed a Poisson distribution with a standard deviation of $\pm 1/\sqrt{N}$ X 100 pct, where N is the number of fibers counted per filter. For a 95 pct confidence limit of ±20 pct (2 standard deviations), 100 fibers must be counted.

For each sample, 100 fields chosen at random were counted. Fibers counted were those longer than 5 μm with aspect ratios of 3:1 or greater. The average number of fibers per field was then determined.

The concentration sampled is determined by the equation

$$\frac{\text{Average fiber count per field X K}}{\text{Sampling rate X time}} = \text{fibers/ml}, \qquad (1)$$

where

$$K = \frac{\text{Filter area}}{\text{Field area}} = \frac{855\ mm^2}{0.0026\ mm^2} = 328{,}800; \qquad (2)$$

sampling rate is in milliliters per minute, and time is in minutes.

The method chosen to provide the best estimate of the ratio control setting for 5 μm fiber length discrimination was to perform a least-squares linear-regression analysis of

$$\overline{X}_{FAM} - \overline{X}_{optical} \text{ versus FAM ratio}, \qquad (3)$$

where $\overline{X}$ = concentration in fibers per milliliter. Table 1 lists the data used for this determination. The coordinate that fulfills the constraint

$$\overline{X}_{FAM} - \overline{X}_{optical} = 3.95 - 1.11 \times \text{FAM ratio} = 0 \quad (4)$$

determines the desired FAM ratio control setting of 3.56 and, as previously explained, is theoretically independent of the fiber-size distribution.

TABLE 1. - Test summary for determination of ratio control setting

Test	$\overline{X}_{FAM}$, fibers/ml	$\overline{X}_{optical}$, fibers/ml	FAM ratio	$\overline{X}_{FAM} - \overline{X}_{optical}$, fibers/ml
1	6.3	7.4	3.50	-1.1
2	2.0	1.3	3.50	.7
3	6.8	3.9	3.50	2.9
4	9.1	11.5	4.00	2.4
5	6.5	7.3	4.00	-.8
6	2.3	1.2	4.00	1.1
7	5.2	8.5	5.00	-3.3
8	5.1	11.8	5.00	-6.7
9	1.6	1.2	5.00	.4
10	1.9	4.9	7.00	-3.0
11	3.2	10.1	7.00	-6.9
12	.5	1.4	7.00	-.9
13	8.5	6.8	2.00	1.7
14	2.9	1.8	2.00	1.1
15	1.0	.7	2.00	.3

After obtaining the FAM ratio control setting, a second series of tests was performed using the FAM to monitor different aerosol concentrations at the same ratio control setting. (Actually, a ratio control setting slightly higher than 3.56 was used for these tests, but this should have had no substantial effect because only an approximate value is needed.) Table 2 summarizes the test results.

TABLE 2. - Least-squares regression lines relating fiber concentrations determined by fibrous aerosol monitor and by optical count

Test unit	$\frac{\overline{X}_{FAM}}{\overline{X}_{optical}}$[1]	n	Sy·x	R^2	S_{slope}
FAM 1	0.74	8	0.64	0.94	0.07
FAM 2	1.22	11	.74	.93	.10

[1]FAM ratio control setting for the tests shown was 3.86.
R^2 = Coefficient of determination.
S_{slope} = uncertainty in slope determination.

To obtain the FAM-optical count correlation, a linear regression forced through the origin was performed. The method chosen for this force fit is different and more precise than simply adding zero pairs to the data and is as follows:

The equations which determine the regression slope and ordinate intercept are

$$y \text{ intercept} = \frac{\Sigma y \Sigma x^2 - \Sigma x \Sigma xy}{n\Sigma x^2 - (\Sigma x)^2} \tag{5}$$

and

$$\text{slope} = \frac{n\Sigma xy - \Sigma x \Sigma y}{n\Sigma x^2 - (\Sigma x)^2} \tag{6}$$

where n = number of data points,

$y = \overline{X}_{FAM}$,

and $x = \overline{X}_{optical}$;

and both x and y are in fibers per milliliter.

Equation 5 is set equal to zero and solved algebraically for Σxy. The resulting equation is then substituted into equation 6 to give the slope of the regression forced through the origin. The equation that results from this substitution is

$$\text{slope} = \frac{n \dfrac{\Sigma y \Sigma x^2}{\Sigma x} - \Sigma x \Sigma y}{n\Sigma x^2 - (\Sigma x)^2} . \tag{7}$$

The standard error of estimate (y on x) is given by

$$Sy \cdot x = \left[\frac{\Sigma (y_i - \hat{y}_i)^2}{n-1} \right]^{1/2} , \tag{8}$$

where $\hat{y}$ = the value predicted from the regression. Constraining the regression through the origin requires the use of the value n-1 in the denominator since there is one degree of freedom, the slope determination.

Figure 4 shows the results of the linear regressions for the two FAM units that were used in this study. The error bars shown along the slope represent the ±10 pct Poisson statistical uncertainties associated with each test. These uncertainties are calculated from the equations

$$\pm 1\sigma(\overline{X}_{FAM}) = \frac{\pm \overline{X}_{FAM}}{(\overline{X}_{FAM} \text{ X } 10 \text{ X counting period})^{1/2}} \tag{9}$$

and $$\pm 1\sigma(\overline{X}_{optical}) = \pm \frac{\sqrt{N}}{N} \overline{X}_{optical} \quad (10)$$

Table 3 summarizes the test statistics.

TABLE 3. - Test summary for linear regressions

Test	$\overline{X}_{optical}$, fibers/ml	N	$\sqrt{N}$	±1σ Poisson uncertainties (optical)	$\overline{X}_{FAM}$, fibers/ml	Counting period, min	±1σ Poisson uncertainties (FAM)
			FAM 1				
1	5.6	103	10.15	0.55	4.9	26	0.14
2	2.0	36	6.00	.33	1.3	27	.07
3	3.1	57	7.55	.41	2.3	26	.09
4	9.2	56	7.48	1.23	7.0	9	.28
5	10.9	100	10.00	1.09	6.7	12	.24
6	7.4	90	9.49	.78	5.3	16	.18
7	5.6	52	7.21	.78	4.7	13	.19
8	.0				0.0		
			FAM 2				
9	3.0	36	6.00	.50	3.8	15	.16
10	4.6	42	6.48	.71	4.9	12	.20
11	2.4	22	4.69	.51	2.8	13	.15
12	7.0	64	8.00	.88	7.2	13	.24
13	1.7	16	4.00	.43	3.2	12	.16
14	1.3	11	3.32	.39	2.1	11	.14
15	.7	6	2.45	.29	.7	12	.08
16	6.2	38	6.16	1.01	8.5	8	.33
17	3.1	28	5.29	.59	3.0	13	.15
18	.3	6	2.45	.12	.7	21	.06
19	.0				.0		

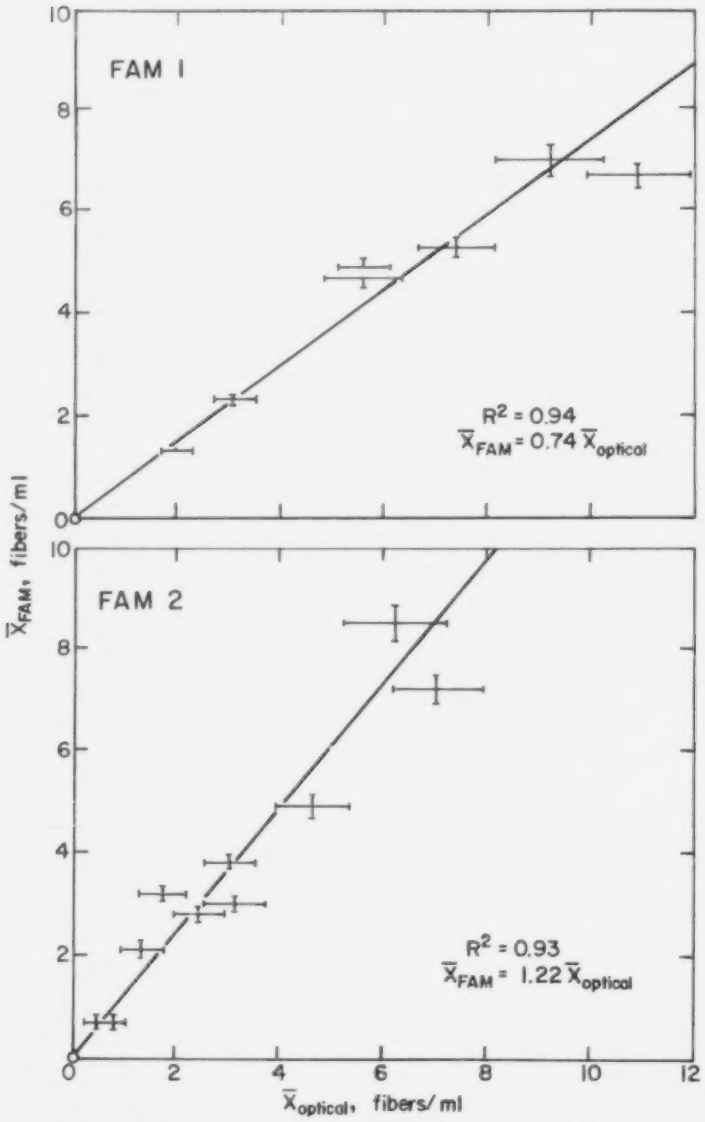

FIGURE 4. - Linear least-squares regression for two fibrous aerosol monitors. (Error bars along both slopes represent the ±10% Poisson uncertainties for each test. For both tests, FAM ratio control settings were 3.86, and amplitude function was 0.20.)

DISCUSSION OF RESULTS

As previously stated, two identical FAM units were used for the tests described in this report. The two units are distinguished in this discussion by the designations FAM 1 and FAM 2.

FAM 1 was initially used for tests to establish the FAM ratio control setting and the FAM-optical count correlation. Although the estimate for the ratio control setting was determined by the least-squares regression to be 3.56, a ratio control setting of 3.86 was used for the correlation tests, due to an error in microscope calibration. However, this small difference, compared to the statistical errors that arise when the optical filter count method is used, is not considered significant with respect to optimum 5-μm fiber-length discrimination.

Subsequent to the initial tests using FAM 1, a second unit, FAM 2 was obtained. A FAM-optical count correlation was then determined for FAM 2, using the same ratio and amplitude function settings as were used in testing FAM 1.

Table 2 and figure 4 show the results for both instruments. Although there appears to be excellent linear correlation with the optical membrane filter count for each instrument, comparison of the two regression lines shows a 65 pct difference between results for FAM 1 and FAM 2. Statistical uncertainty in the slope determination for each regression line (table 2) suggests that approximately 30 pct of this variation can be attributed to regression

fitting errors. One possible explanation for at least a portion of the remaining 35 pct difference may be the use of the same control settings for both instruments. Internal adjustment of the photomultiplier sensitivity may be sufficiently different in the two instruments (8) to warrant predetermination of the 5-μm fiber-length discrimination FAM ratio control setting for each instrument.

However, it was noticed in the early stages of testing that FAM 1 occasionally counted fibers erratically--more erratically than would be expected if the cause was fluctuations in aerosol concentration. This erratic behavior was most apparent after the instrument had functioned continuously for 1 to 3 hours, indicating a possible electrical component breakdown. Since there were no changes in the diagnostic output signals, the malfunction could not be diagnosed, although a temperature-dependent malfunction appears quite probable.

To observe the effect of continuous operation, a test comparing FAM 1 readings with optical count data was performed. The test consisted of two 1-hour runs separated by a period of 3 hours. Prior to the second test, the FAM 1 and the aerosol generator were left on during the 3-hour period. The first 1-hour run yielded a FAM reading of 6.5 fibers/ml, compared with an optical count determination of 8.5 fibers/ml for the same run. The difference between these two determinations was 24 pct. The second 1-hour test yielded a FAM reading of 2.9 fibers/ml, compared with an optical count determination of 15.2 fibers/ml. The difference in the FAM and optical determinations for the second test was 81 pct. Thus, it was shown that this particular unit, FAM 1, did not function properly after extended operation.

In order to minimize--if not eliminate--this effect, none of the tests was run for more than 1 hour; most lasted for periods ranging from 15 to 30 min. Furthermore, fan-forced air was used to cool the instrument case during all tests. Although these precautions were taken, it is not certain that the effect believed to have been caused by heating of the unit was completely eliminated during testing. This may be a reasonable explanation for the remaining 35 pct difference between readings from the two units, particularly since the FAM which exhibited erratic behavior gave lower fiber concentration readings. FAM 2 was not tested for the possibility of erratic behavior after continuous operation. (From this point on, FAM is again used in a general sense that does not distinguish between FAM 1 and FAM 2, but instead refers to the performance of either or both of the units.)

A particulate-free, well-defined fiber aerosol was used to test the FAM in order to isolate the FAM fiber response from the particulate response. Assuming that a FAM-optical count correlation could be achieved, it would then be necessary to determine the FAM response to particulates in the absence of fibers. In order to make this determination, the fibrous-aerosol generator was removed from the dust chamber and replaced with a Wright dust feeder containing Arizona road dust (ARD), a standard test dust. The objective was to gravimetrically determine the maximum dust concentration that would not--in the absence of fibers--produce FAM counts.

As a preliminary, a GCA RDM 301 dust monitor and a GCA 201 dust monitor were allowed to sample the same aerosol that the FAM sampled. The FAM and the GCA 201 sampled total dust while the GCA 301 sampled respirable dust. The FAM produced counts very rapidly, as if an excessive fiber concentration was present. However, when the rotating electric field was disabled, the FAM would not register any counts. Respirable concentrations ranged from approximately 0.4 to 2.1 mg/m^3. Total dust concentrations ranged from approximately 10 to 40 mg/m^3. To understand this effect, the relationship between mass concentration and number concentration was established for ARD.

Assuming a number concentration of 30 particles/ml, which is sufficient to produce fiber-count saturations, a few simple calculations indicate that the corresponding mass concentrations are approximately 5.1 mg/m^3 for 5.0-μm ARD, 0.33 mg/m^3 for 2.0-μm ARD, and 0.04 mg/m^3 for 1.0-μm ARD. Thus, it is seen that as particle size becomes smaller, a 30-particle/ml number concentration corresponds to an increasingly smaller mass concentration. Assuming that ARD particulates behave like fibers, a smaller mass concentration consisting of smaller particles will produce a FAM fiber-count saturation.

To determine whether the FAM counts resulted from particulate overload or whether the counts indicated that the particulate was behaving like a fibrous aerosol, the test was carried one step further by substituting 20-μm spheres of ragweed pollen for ARD. The pollen was suspended in filtered isopropyl alcohol, and a hand nebulizer was used to introduce the pollen into the dust chamber. No counts were registered--not even for pollen concentrations that were sufficient to overload the FAM photomultiplier detector by more than 10 times the overload produced by large individual fibers. Thus, it is apparent that an ARD particulate produces light-scattering signals that are very similar to fiber-produced signals. This similarity is attributed to the shape irregularities of ARD, even though the aspect ratio for ARD particulates is considerably smaller than the aspect ratio for fibers. Identical findings have recently been reported by GCA (8). GCA's results also show that fusain, or fibrous, coal will produce FAM counts but that vitrain, or particulate, coal will not.

Analysis of the theory of FAM operation shows that particles with smaller aspect ratios can synchronously follow the rotating electric field much more easily than particles with larger aspect ratios can. This implies that even small shape irregularities, such as those encountered in normal dust measurements, may result in particulate rotations.

RECOMMENDATIONS AND CONCLUSIONS

Although the FAM shows a very good linear correlation with the NIOSH-approved optical membrane filter count on an instrument-to-instrument basis for concentrations ranging from 0 to 10 fibers/ml, more extensive testing is required, including tests using fibers that are more irregularly shaped than those used in this research so that calibration variations can be determined.

Non-fibrous particulates frequently have L:D aspect ratios of 3:1, but fibers invariably have substantially larger aspect ratios. The inability of the FAM to discriminate between fibers and certain types of particles that may appear as fibers shows the need to establish stricter fiber criteria (17) or an instrument that can adequately discriminate with respect to existing criteria.

Although laboratory tests showed that the FAM estimated fiber concentrations within ±25 pct of the FAM-optical count correlation, field performance has been considerably poorer (5), with a much larger degree of scatter in the data.

The following conclusions may be drawn from this study:

1. Laboratory evaluation of the FAM yields a good linear correlation with the NIOSH-approved optical membrane filter count in the range from 0 to 10 fibers/ml.

2. Instrument-to-instrument variability appears to be large enough to warrant individual instrument calibration for both 5-μm fiber-length discrimination and optical correlation.

3. The FAM is sensitive to particulates that are sufficiently irregular in shape to meet existing fiber criteria.

REFERENCES

1. Bayless, D., J. Dement, and J. K. Wagoner. Mortality Patterns Among Fibrous Glass Production Workers Provisional Report. Proc. Occup. Exposure to Fibrous Glass. College Park, Md., June 26-27, 1974. HEW Pub. 76-151, 1976, pp. 349-363.

2. Becklake, M. R. Asbestos-Related Diseases of the Lung and Other Organs: Their Epidemiology and Implications for Clinical Practice. Am. Rev. Respir. Disease, v. 114, 1976, pp. 187-227.

3. Birkhoff, R. D., J. C. Ashley, H. H. Hubbell, Jr., and L. C. Emerson. Light Scattering From Micron-Size Fibers. Opt. Soc. Am. J., v. 67, No. 4, 1977, pp. 564-569.

4. Bruckman, L., R. A. Rubino, and B. Christine. Asbestos and Mesothelioma Incidence in Connecticut. Air Pollut. Control Assoc. J., v. 27, No. 2, 1977, pp. 121-126.

5. GCA Precision Scientific Group. Comparison of GCA's Model FAM Fibrous Aerosol Monitor to NIOSH's Recommended Procedure for Asbestos Sampling and Microscopic Counting. Unpublished report available from P. Lilienfeld, GCA Technology Div. of GCA Corp.,Bedford, Mass.

6. Gibbs, G. W., P. Baron, S. T. Beckett, R. Dillen, R. S. J. DuToit, M. Koponen, and K. Robock. A Summary of Asbestos Fibre Counting Experience in Seven Countries. Ann. Occup. Hyg., v. 20, No. 4, 1977, pp. 321-332.

7. Lilienfeld, P., and P. B. Elterman. Development and Fabrication of a Prototype Fibrous Aerosol Monitor (FAM). Contract 210-76-0110 Final Report, HEW (NIOSH) Pub. 78-125, 1977, pp. 2-26.

8. Lilienfeld, P. Private communication, 1979. Available from S. J. Page, Bureau of Mines, Pittsburgh, Pa., or from P. Lilienfeld, GCA Technology Div. of GCA Corp., Bedford, Mass.

9. Rajhans, G. S. Fibrous Dust--Its Measurement and Control. CIMM Bull., v. 63, No. 100, August 1970, pp. 900-910.

10. _____. Here's an Update on Asbestos... Occup. Health and Safety, v. 46, No. 6, 1977, pp. 38-43.

11. Schepers, G. W. H. The Comparative Pathogenicity of Inhaled Fibrous Glass Dust. Proc. Occup. Exposure to Fibrous Glass. College Park, Md., June 26-27, 1974. HEW Pub. 76-151, 1976, pp. 265-341.

12. Spurny, K. R., C. Boose, D. Hochrainer, and F. J. Mönig. A Note on the Dispersing of Fibrous Powders. Ann. Occup. Hyg., v. 19, No. 1, 1976, pp. 85-87.

13. Stoimenova, M. W. Electric Light Scattering by Cylinder-Symmetrical Particles. Colloid Interface Sci. J., v. 53, No. 1, 1975, pp. 42-49.

14. Timbrell, V., A. W. Hyatt, and J. W. Skidmore. A Simple Dispenser for Generating Dust Clouds From Standard Reference Samples of Asbestos. Ann. Occup. Hyg., v. 11, No. 4, 1968, pp. 273-281.

15. U.S. Department of Health, Education, and Welfare; National Institute for Occupational Safety and Health. Criteria for a Recommended Standard... Occupational Exposure to Asbestos. HSM 72-10267, 1972, pp. VIII-1-VIII-8.

16. U.S. Department of Labor, Occupational Safety and Health Administration. Regulations, Toxic and Hazardous Substances. Federal Register, v. 36, No. 234, Dec. 7, 1971, pp. 2342-2343.

17. Winer, A. A., and M. Cossette. The Effect of Aspect Ratio on Fiber Counts: A Preliminary Study. Presented at Workshop No. 1, International Conference on: The Scientific Basis for the Public Control of Environmental Health Habits. New York, N.Y., June 26, 1978.

APPENDIX A.--LABORATORY TEST FACILITY

Fibrous Aerosol Generation

A number of techniques for generating fibrous aerosols have been described in the literature, including the vibrating-bed generator (12) and the Timbrell-type generator (14). A new generation procedure developed by the Bureau yields discrete, unagglomerated fibers in the concentration range from 0 to 10 fibers/ml. Fiber lengths typically range from about 2 μm to 30 μm with a small percentage of fibers longer than 50 μm.

The fiber material used in this study was 99+ pct pure anthophyllite asbestos and was selected for two reasons. First, it was desirable to know how the instrument performed in a fibrous particulate only. Second, anthophyllite is typically a well-defined, uniform cylindrical shape. The use of anthophyllite, which meets both these criteria, provided nearly ideal test conditions for FAM evaluation. Figure A-1 shows scanning electron microscope photographs of a typical reference test sample A compared with an actual field sample B of chrysotile asbestos.

The 99+ pct-pure anthophyllite fiber dust was contained in a blender operating at approximately 10,000 rev/min (fig. A-2). System airflow was

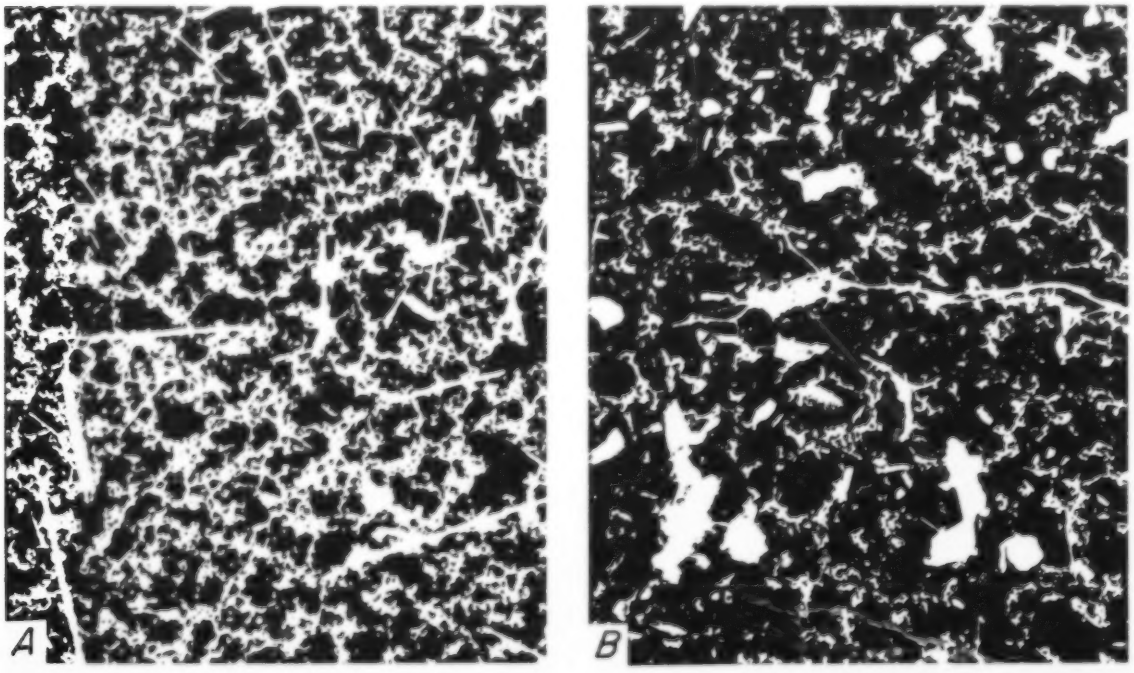

FIGURE A-1. - Fibrous aerosols as shown in scanning electron photomicrographs (X 1,000). *A*, Laboratory-generated sample; *B*, field sample.

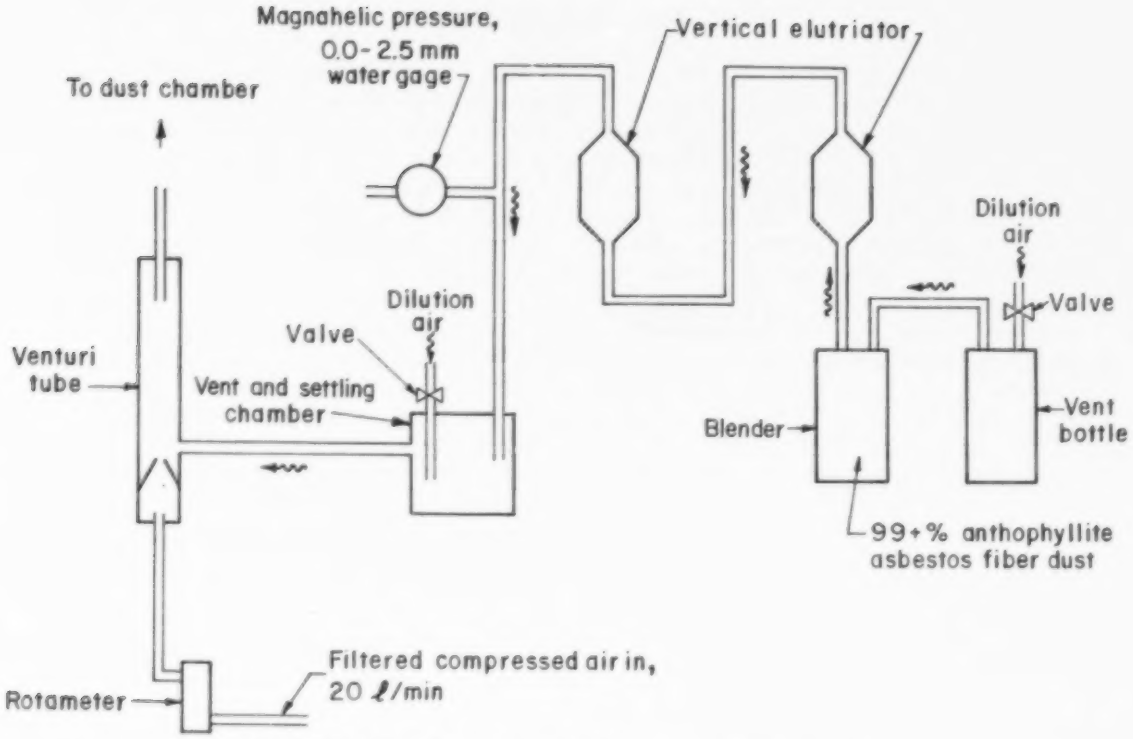

FIGURE A-2. - Flow chart for fiber generation system.

created by introducing filtered, compressed air at approximately 20 1/min through a venturi tube. The venturi high-velocity throat created a negative pressure in the aerosol generator, resulting in a net airflow. Two vertical elutriators and a settling chamber were used that allowed only smaller fibers to be entrained. By varying airflow input into the venturi, the system airflow could be varied to allow a variable, approximate upper limit on the fiber length introduced into the test chamber. Air was introduced at the settling chamber to dilute the fiber concentration passing the elutriators. A magnahelic differential-pressure gage downstream of the elutriators served as a sensitive monitor of system airflow. A negative pressure between 0.0 and 2.5 mm water gage proved sufficient for aerosol generation. Upon reaching the venturi, the fiber-laden air was transported to the test dust chamber via the venturi main airflow.

The long-term fiber-concentration stability (>1 hour) of this system is not believed to be good, although this could not be determined. However, 15- to 30-min periods were quite sufficient for reference sample collection.

Test Dust Chamber

Figure 3 is a schematic of the test dust chamber. The chamber is constructed of 3.2-mm aluminum and, excluding the conical section, has 0.28 m^3 of sampling space accessible through a 25-port sampling manifold mounted on the side of the chamber. The chamber bottom consists of a 99.9+ pct-efficient[1] high efficiency particulate air (HEPA) filter. This design gives a more uniform vertical velocity profile through the chamber and eliminates any pressurization within the chamber. Assuming a 20-l/min net flow-rate input, the flow velocity is approximately 6.1 cm/min.

Fiber-laden air is transported via the venturi tube and enters the top of the test chamber as shown in figure 3. Filtered air is simultaneously introduced axially opposite and into the fiber-laden airstream at a constant rate, typically about 5 l/min. This serves to disperse the dust aerosol, which then expands to fill the conical section mounted above the chamber. The aerosol then enters the test chamber with uniform spatial distribution.

[1]DOP, or di-octyl pthalate, efficiency at 600 cfm, 0.88 inch water gage.

APPENDIX B.--TEST DATA SHEET

Title: FAM-1 Calibration		Date: Jan. 8, 1979 (afternoon)	
Pump flow	2.00 l/min	Sample No.	10-1
FAM flow	2.0 l/min	Chamber inlet	No. 1
Filter sample time	30 minutes	FAM ratio	3.86
Dust flow	50 mm	FAM amplitude	0.20
Air flow	20 mm	Fiber type	Anthophyllite asbestos
Critical orifice	No. 1: 2.00 l/min	Laser VDC	5.6
		Field VDC	4100

FAM readings--fibers/ml, 1-minute count periods

1. 3.3	11. 5.2**	21. 5.6
2. 5.2	12. 5.2	22. 5.1
3. 5.7	13. 5.2	23. 4.9
4. 6.9	14. 5.2	24. 5.3
5. 5.7	15. 5.2	25. 3.7
6. 4.1	16. 5.2	26. 3.9
7. 6.0	17. 5.2	27. 3.3
8. 0.0*	18. 5.2	28. 0.1*
9. 4.9	19. 5.2	
10. 6.8	20. 5.2	

Comments

*: Background count--rotating field disabled.

**: 11 through 20 represent 10-minute sampling period.

$\overline{X}_{FAM}$: 5.0 fibers/ml Optical Count: 5.6 fibers/ml

Background: 0.1 fibers/ml

☆U.S. GOVERNMENT PRINTING OFFICE: 1980-603-102/83 INT.-BU.OF MINES,PGH.,PA. 24749